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The efficacy of temporal processing training to improve phonological awareness among dyslexic and normal reading students

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Abstract

One of the leading theories for dyslexia suggests that it is the result of a difficulty in auditory temporal processing (ATP). This theory, as well as others, is supported by studies showing group differences and correlation between phonological awareness and ATP. However, these studies do not provide causal relationship. In the current study we aimed to test causal relationship between ATP and phonological awareness by comparing the performance of dyslexic and normal reader students in phonological awareness tasks before and after a short-term (5-days) training in either temporal processing (dichotic temporal order judgment, TOJ), non-temporal processing (intensity discrimination), or no training. TOJ training resulted in significant reduction of TOJ threshold and increase in phonological awareness tasks' scores. Intensity discrimination training resulted in a decrease of intensity discrimination threshold, but with no change in phonological awareness tasks. Those who had no training, had no change in TOJ and intensity discrimination thresholds, as well as in the phonological awareness tasks. These results show that (1) a short-term training in temporal processing with no other perceptual cues for adult dyslexic and normal readers can be efficient in improving their phonological awareness; and (2) phonological awareness (dis)ability has causal relationship to ATP.

Keywords: Dyslexia; Training; Auditory temporal processing (ATP); Causality
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Developmental dyslexia reflects a specific difficulty to acquire age-appropriate reading skills in otherwise normally developing children (Curtin, Manis, & Siedenberg, 2001; Stanovich, 1988; Vellutino, 1979). Developmental dyslexia affects 5% to 10% of the school-age children and is considered to have a strong hereditary component (Becker et al., 2013). Although diagnosis and intervention for developmental dyslexia focus on children, the reading and writing difficulties continue into adulthood (Hoien & Lundberg, 2000). The literature on dyslexia indicates different subtypes which have various cognitive-linguistic processing difficulties (e.g., Jednoróg, Gawron, Marchewka, Heim, & Grabowska, 2013; van Ermingen-Marbach, Pape-Neumann, Grande, Grabowska, & Heim, 2013). In the current study we focused on phonological dyslexia, which is considered to be the most prevalent and has been extensively studied. Debate abounds regarding the mechanisms underlying phonological dyslexia (e.g., Ramus, 2003), although consensus exists regarding its neurological nature. One of the major theories regarding dyslexia is auditory temporal processing (ATP) deficit (Ben-Artzi, Fostick, & Babkoff, 2005; Fostick, Bar-El, & Ram-Tsur, 2012a; Reed, 1989; Tallal, 1980). This hypothesis posits that reading impairment is caused by a fundamental perceptual deficit in processing rapid, auditory or visual stimuli (Ben-Artzi et al., 2005; Ram-Tsur, Faust, & Zivotofsky, 2006, 2008; Tallal, 1980). According to this model, speech, which is composed of brief stimuli presented rapidly, is especially vulnerable to deficit in temporal processing since this impairment reduces the ability of the individual to perceive critical elements in the speech stream accurately. This inability,
in turn, disrupts the establishment of a stable phonological code (Ben-Artzi et al., 2005; Meyler & Breznitz, 2005; Tallal & Piercy, 1973a).

Different studies point to an association between difficulty in temporal processing and dyslexia. Since the classical studies by Tallal (1980), she and others (e.g., Tallal & Piercy, 1973a,b; 1974; 1975; Reed, 1989) showed that children with reading difficulties needed larger intervals between sounds in order to correctly reproduce their order. Following these findings, many studies report group difference in reading and phonological awareness, along with temporal processing, between dyslexic and non-dyslexic children and adult participants (e.g., Ben-Artzi et al., 2005; Breier et al., 2001; Chung et al., 2008; Fostick et al., 2012a; Fostick, Bar-El, & Ram-Tsur, 2012b; Murphy & Schochat, 2009; Van Ingelghem et al., 2001), although different studies do not show these differences (e.g., Mody, Studdert-Kennedy, & Brady, 1997; Studdert-Kennedy & Mody, 1995). Studies using imaging techniques have also shown group differences in temporal processing between dyslexic and normal readers (e.g., Belin et al., 1998; Brosnan et al., 2002; Cohen-Mimran, 2006; Gaab, Gabrieli, Deutsch, Tallal, & Temple, 2007; Meng et al., 2005; Steinbrink, Ackermann, Lachmann, & Riecker, 2009; Temple et al., 2001). Although all these studies show a clear difference in temporal processing between those who exhibit reading and phonological difficulties and those who do not, group differences cannot point to a connection between the two variables.

There are, however, studies that report a more direct association between reading, phonological awareness and temporal processing among dyslexic and normal readers (e.g., Ahissar, Protopapas, Reid, & Merzenich, 2000; Ben-Artzi et al., 2005; Cohen-Mimran, 2006; Fostick et al., 2012b; Heiervang, Stevenson, & Hugdahl, 2002; Tallal, 1980). These studies found significant correlations between performance on
reading and phonological awareness tasks and the temporal processing ability. For example, Tallal (1980) reports a correlation of .81 between errors made by reading-delayed children on pseudowords reading and auditory rate processing tasks, although Heiervang et al. (2002) found a correlation of only .38 for similar tasks. Similarly, Fostick et al. (2012b) showed correlations of -.38 between accuracy rate of reading regular words and Temporal Order Judgment (TOJ) threshold of dyslexic readers. Ahissar et al. (2000) reported correlations of -.36 to -.44 between thresholds in several auditory processing tasks and reading measures. In contrast, Ben-Artzi et al. (2005) did not find such correlations for the dyslexic readers group, but only for the normal readers (.47 between dichotic TOJ reaction time and errors made while reading a passage) and for the entire sample (.28 and .31 between dichotic and spectral TOJ reaction time and reading errors).

Although the correlational studies show shared variance between reading and phonological awareness and temporal processing, correlational studies cannot point to causality for main two reasons. First, the order of variables was not controlled; thus, we cannot say which caused the other (the chicken-and-egg problem). Second, it is possible that a third factor affected both reading and phonological ability and temporal processing, with no direct relationship between them (the third variable problem).

Training studies, however, do show causality. These studies demonstrate that the manipulation of one variable, i.e., temporal processing, results in a change in the other variable, i.e., reading and phonological processing (for a review, see Loo, Bamiou, Campbell, & Luxon, 2010). In this regard, these studies indeed show a causal relationship between temporal processing and reading and phonological abilities. However, they have some drawbacks. First, some of these studies (e.g.,
McArthur, Ellis, Atkinson, & Coltheart, 2008; Strehlow et al., 2006; Veuillet, Magnan, Ecalle, Thai-Van, & Collet, 2007) test training techniques that can only be used in the clinic or the laboratory and are not fit for daily training undertaken independently by the participant. Second, some of the training methods (e.g., those applied by Chermak & Musiek, 2007) include only basic auditory processing (such as discrimination of sounds with and without background noise) and lack any element of temporal processing, which is the focus of the ATP theory for dyslexia. Moreover, problematic stimuli are used in some of the training methods (e.g., Cohen et al., 2005; Gaab et al., 2007; Gillam et al., 2008; Given, Wasserman, Chari, Beattie, & Eden, 2008; Hook, Macaruso, & Jones, 2001; Stevens, Fanning, Coch, Sanders, & Neville, 2008; Temple et al., 2003; Valentine, Hedrick, & Swanson, 2006). These studies show training with linguistic stimuli or non-linguistic sounds that have different frequencies or other acoustic structures that resemble speech sounds. The problem is that training programs with such stimuli do not test the effect of temporal training per se. Temporal processing refers to the ability to process stimuli differing on the time domain. When adding other acoustic signals, like intensity or frequency differences, additional cues – not necessarily the temporal cue – can be used for processing the training stimuli. Indeed, several researchers have suggested previously that the perception of temporal stimuli can be accomplished in different ways, and not necessarily using the temporal cues (e.g., Ben-Artzi et al., 2005; Broadbent & Ladefoged, 1959; Warren & Ackroff, 1976). Recently, we suggested that different perceptual mechanisms are used when judging the temporal order of two tones that differ in their frequency, as opposed to two tones with identical acoustical features (Fostick & Babkoff, 2013). The last drawback of the training programs previously utilized for evaluations is that they all were tested on children. None of the studies
examining auditory temporal processing training for dyslexic readers were carried out on adults. Therefore, it is not clear whether young adults can benefit from such training programs.

The present study was designed in order to overcome these three shortcomings. In this study we aimed to test the training effect of TOJ training, as compared with intensity discrimination or no training for phonological awareness, using (1) simple tasks that can be installed on the participant's personal computer; (2) temporal processing task that includes order judgment of two identical pure tones, such that no frequency of spectral information is available; and (3) study participants comprised of students between the ages of 20 and 35, including both dyslexic and normal reader.
Method

Participants
Sixty-four dyslexic readers and 47 normal readers participated in the study and were divided into three groups: with TOJ training, with intensity discrimination training, and with no training at all (Table 1). All participants were native Hebrew speakers and had hearing levels of $\leq 20$ dB HL. Dyslexic readers were diagnosed as having phonological dyslexia prior to and independent of the study by a specialists and were recruited to the study after presenting a documented diagnosis that included testing of reading, writing, phonological awareness, naming, and rhyming. Normal readers were students that reported on no past or current reading difficulties. Dyslexic readers were found to be lower than normal readers on the phonological awareness measures at the beginning of the study.

Tasks and stimuli
The sounds in the psychoacoustic tasks were delivered in an equal intensity of 40 dB above each participants' own hearing threshold (40 dB SL). In order to measure participants' hearing thresholds, they were asked to perform a task of absolute threshold in which they received a 1 kHz, 15 msec pure tone with 1 msec rise/fall time and indicated whether they heard it or not. The absolute threshold task was performed in a two-down-one-up adaptive procedure. The task terminated after ten reversals, and the threshold was calculated as the average of the last eight reversals.

Temporal order judgment. In each trial, two 1-kHz 40 dB SL pure tones were presented, with 1 msec rise/fall time. One tone was presented to each ear, separated by temporal intervals. The participants were required to press the appropriate keys on a computer keyboard corresponding to the order of stimulation between ears (i.e., the
temporal order of the tones, right-left, or left-right), which varied randomly. Tones were separated by an inter-stimulus interval (ISI, the time between the offset of the first stimulus presented to the "lead" ear and the onset of the second stimulus presented to the "lag" ear), which varied in a two-down-one-up adaptive procedure. The initial ISI of 250 msec was changed according to the participants' responses in the following step sizes: steps of 25 msec for ISIs of 250 to 100; steps of 10 msec for ISIs of 100 to 50 msec; steps of 5 msec for ISIs of 50 to 15 msec; and steps of 2.5 msec for ISIs of less than 15 msec. The experiment continued for ten reversals, and the TOJ threshold was calculated as the average of the last eight reversals. The experiment was preceded with a practice session in which 30 pairs of stimuli were presented with an ISI of 250 msec, and participants needed to reproduce the order in which they were heard. They received feedback for each response in the practice session, but no feedback was provided during the experimental session. Practice sessions usually resulted in above 85% accuracy rate.

*Intensity discrimination.* Participants were presented in each trial with a pair of 500 msec duration, 1 kHz pure tones with 1 msec rise/fall time, separated by 100 msec. In each pair, one tone was presented at 40 dB SL, and the other tone was softer. Participants were required to indicate whether the two tones in each pair were the same or different in intensity. The order of the two tones varied randomly, with the 40 dB SL appearing first in about half of the trials and second in the other half. Tone intensity deltas were changed in a two-down-one-up adaptive procedure, starting with the largest intensity delta of 20 dB, and going down with the following step sizes: steps of 5 dB for intensity deltas of 20 to 10 dB; steps of 1 dB for intensity deltas of 10 to 5 dB; and steps of 0.5 dB for intensity deltas of less than 5 dB. The experiment continued for ten reversals, and the intensity discrimination threshold was calculated
as the average of the last eight rounds. The experiment was preceded with a practice session in which stimulus pairs were presented with intensity deltas of 20 and 0 dB, repeating 16 times each, for which the participants needed to say whether the tones were the same or different in their intensity and received feedback for each response. No feedback was provided during the experimental session. Practice sessions usually resulted in above 85% accuracy rate.

_Pseudoword reading._ A list of 86 solitary, dotted pseudowords with a high spelling-to-sound correspondence (Frost, 1994) was presented to participants. The words were built according to the Hebrew grammar with a length of 3 to 6 letters. The participants were required to read the words as rapidly and correctly as possible during one minute. Participants’ scores reflect the number of words per minute that they read correctly (Fostick et al., 2012a,b; Shatil, 1995). As the participants in the study were students, therefore were expected to be familiar with reading, this task measured their ability to read without using any context cues.

_Phoneme deletion._ In each trial, participants were presented with a meaningful Hebrew word consisted of 2 to 3 phonemes read aloud by the experimenter. The participants were instructed to repeat each word after hearing it and omit one of its phonemes. Twenty meaningful Hebrew words were presented, and the place of the omitted phoneme was changed (it appeared in the beginning, middle or end of word), creating different difficulty levels for the task. Accuracy and reaction time for providing correct responses were recorded (Fostick et al., 2012a,b; Share, 1997). This task measures the participants' ability to manipulate speech sounds in order to reflect their phonological awareness ability.

_Procedure_
All participants were tested individually at their homes, in a quiet room less than 40 dB SPL. On Day 1 and Day 5, participants completed the full test battery, including absolute threshold measurement, TOJ, intensity discrimination, pseudowords reading and phoneme deletion tasks. The tests were performed in a random order for each participant, with the absolute threshold test preceding the other two psychoacoustic tasks. On Days 2 to 4, participants from the TOJ and intensity discrimination training groups took the absolute threshold test and engaged in the training task (either TOJ or intensity discrimination). Prior to recruitment the participants were asked (telephonically) for their native language and whether any hearing difficulties are present. The Institutional Review Board approved the study, and participants signed their informed consent on Day 1 prior to experimentation.
Results

*Psychoacoustic training*

Figure 1 presents TOJ data and Figure 2 presents intensity discrimination data for the study groups. Data for Days 1 to 5 is presented for the groups that received training and data for Day 1 and Day 5 only is presented for the other groups. Two-way repeated measure ANOVAs were conducted separately for the groups that were trained at the TOJ and the intensity discrimination tasks, with the day of training (1 to 5) functioning as the within-subjects variable, and reading groups (dyslexic vs. normal readers) as the between-subjects variable.

For the groups that underwent TOJ training, significant effects were found for day of training \((F(4,140) = 108.90, p<.001)\) and for group \((F(5,170)=15.90, p<.001)\), but not for interaction \((F(5,170)=.952, p>.05)\). These effects show, as expected, significant difference between dyslexic and normal readers in TOJ threshold and a significant reduction in TOJ threshold over the course of training – from Day 1 to Day 5. However, the lack of training by group interaction suggests that the difference between dyslexic and normal readers did not change with TOJ training. For the groups who had intensity discrimination training, a significant effect was found for day of training \((F(4,140)= 1.029, p<.05)\), but no effect for group \((F(5,175)=.180)\) or interaction \((F(5,175)=.123)\). These results show a reduction in intensity discrimination threshold through training, but no group differences in intensity discrimination.

*Before vs. after training: Psychoacoustics and phonological awareness*

Three-way repeated measure ANOVAs were conducted separately for each of the study measures on all participants, with testing day (1 vs. 5) functioning as the withi-
subjects variable and reading group (dyslexic vs. normal readers) and training type (TOJ, intensity discrimination, or no training) serving as the between-subjects variables. For TOJ data, significant main effects were found for testing day ($F_{(2,200)}=122.45$, $p<.001$) and reading group ($F_{(1,100)}=92.47$, $p<.001$), but not for training type ($F_{(5,500)}=.896$, $p>.05$), showing again a significant difference between dyslexic and normal readers and a reduction in TOJ threshold from Day 1 to Day 5, but no difference between training groups. In addition, significant day by training group interaction was found ($F_{(1,100)}=22.75$, $p<.01$), but no day by reading group, training group by reading group, or day by training group by reading group interactions ($F_{(1,100)}=.253$, $p>.05$; $F_{(2,200)}=.184$, $p>.05$; $F_{(2,200)}=.343$, $p>.05$, respectively). Post-hoc analyses revealed significant difference between dyslexic readers with TOJ training and the other dyslexic readers (who received intensity discrimination training or no training) at Day 3 ($p<.01$), 4 ($p<.001$) and 5 ($p<.001$). Significant differences were also found between normal readers with TOJ training and the other normal reading groups (who underwent intensity discrimination training or no training) at Days 4 ($p<.01$) and 5 ($p<.001$).

For intensity discrimination data, no main effects were found for day ($F_{(1,100)}=.68$, $p>.05$), reading group ($F_{(1,100)}=.57$, $p>.05$), or training group ($F_{(2,200)}=.34$, $p>.05$). Significant day by training group interaction was found ($F_{(1,100)}=4.75$, $p<.05$), but no day by reading group, reading group by training group, or day by reading group by training group interactions appeared ($F_{(1,100)}=.42$, $p>.05$; $F_{(2,200)}=.28$, $p>.05$; $F_{(2,200)}=.16$, $p>.05$, respectively).

Figure 3 presents data from phonological awareness measures for all study groups on Days 1 and 5. A significant effect for group was found in all phonological awareness tasks (pseudoword reading: $F_{(1,100)}=178.45$ $p<.001$; phoneme deletion...
accuracy: $F_{(1,100)}=5.60, p<.05$; phoneme deletion reaction time: $F_{(1,100)}=9.32, p<.01$). Measurement day was also found to have a significant effect, but only for pseudoword reading ($F_{(1,100)}=15.90, p<.001$) and phonological awareness reaction time ($F_{(1,100)}=21.53, p<.001$). In addition, significant day by training group interaction was found, but again for pseudoword reading and phonological awareness reaction time only ($F_{(2,200)}=22.87, p<.001$ and $F_{(2,200)}=28.63, p<.001$, respectively). No day by reading group ($F_{(1,100)}=.875, p>.05$), reading group by training group ($F_{(2,200)}=.623, p>.05$), or day by reading group by training group ($F_{(2,200)}=.382, p>.05$) interactions were found for any of the phonological awareness tasks.

In order to compare the effect of training between different tasks, the percentage of change from Days 1 to 5 was calculated ($\text{performance on Day 5 - performance on Day 1}/\text{performance on Day 1}$). Figure 4 presents the percentage of change for each task by group. A two-way repeated-measure ANOVA was carried out on the absolute values of the percentage of change data, with task (TOJ, intensity discrimination, pseudoword reading, phoneme deletion accuracy, and phoneme deletion reaction time) serving as the within-subjects variable and study group functioning as the between-subjects variable. The results revealed significant main effects for task ($F_{(4,400)}=183.56, p<.001$) and study group ($F_{(5,500)}=120.89, p<.001$), and task by study groups interaction ($F_{(5,500)}=52.37, p<.001$). ANOVA between tasks for each group separately showed a significant task effect for dyslexic and normal readers who underwent TOJ training ($F_{(4,252)}=12.63, p<.001$ and $F_{(4,184)}=15.86, p<.001$, respectively), and marginal effect for dyslexic and normal readers who received intensity discrimination training ($F_{(4,252)}=2.13, p=.05$ and $F_{(4,184)}=1.06, p<.06$, respectively), but no effect for dyslexic and normal readers who did not engage in any training ($F_{(4,252)}=.813, p>.05$ and $F_{(4,184)}=.96, p>.05$, respectively).
Post-hoc analysis showed a similar change for dyslexic readers who underwent TOJ training regarding TOJ threshold (30%) and pseudoword reading (34%, \(p > .05\)), which was significantly larger than their change on phoneme deletion reaction time (16%, \(p < .01\)), phoneme deletion accuracy (7%, \(p < .001\)), and intensity discrimination (\(p < .001\)). Normal readers who received TOJ training demonstrated similar change on pseudoword reading (16%) and phoneme deletion reaction time (16%, \(p > .05\)). This change was significantly smaller than their change in TOJ threshold (33%, \(p < .001\)) and larger than the change in intensity discrimination (3%, \(p < .001\)) and phoneme deletion accuracy (1%, \(p < .001\)), which were similar (\(p > .05\)).

Both dyslexic and normal readers who underwent intensity discrimination training showed a significantly larger change in intensity discrimination threshold (17% and 13%, respectively) than in TOJ threshold (6%, \(p < .01\) and 1%, \(p < .01\), respectively), pseudoword reading (6%, \(p < .01\) and 3%, \(p < .01\), respectively), phoneme deletion accuracy (3%, \(p < .01\) and 2%, \(p < .01\), respectively) and phoneme deletion reaction time (4%, \(p < .01\) and 2%, \(p < .01\), respectively) – all of which demonstrated a similar rate of change (\(p > .05\)). Dyslexic and normal readers who received no training whatsoever showed no difference in change values between all tasks (\(p > .05\) for all tasks, for both dyslexic and normal readers).
Discussion

TOJ training using a simple computer-based task that does not include any frequency or spectral information improved both dyslexic and normally reading students' scores in phonological awareness. No improvement was evident when dyslexic and normal readers were not trained or received a non-temporal (intensity discrimination) training. These results (1) support the ATP theory for dyslexia and can serve as evidence for a causal relationship between temporal resolution and reading and phonological awareness, and (2) show that dyslexia-related perceptual deficit can be specific to temporal resolution, as no effect was found for training with non-temporal tasks. The relationship between ATP and reading and phonological awareness was found to be causal, however not conclusive. As reading is based on several abilities that can each be interfered and cause dyslexia, additional abilities should be isolated and tested in training design, similar to the current study.

The ATP theory argues that phonological deficits exhibited by dyslexic readers are caused by a more general perceptual deficit. This deficit lies with difficulty in perceiving rapid stimuli (Ben-Artzi et al., 2005; Fostick et al., 2012a,b; Reed, 1989; Tallal, 1980). The ATP theory focuses on the auditory modality; however, studies also show that dyslectic readers encounter difficulties in temporal processing in the visual and tactile modalities as well (Grant, Zangaladze, Thiagarajah, & Sathian, 1999; Laasonen, Service, & Virsu, 2001; McLean, Stuart, Coltheart, & Castles, 2011; Power, Mead, Barnes, & Goswami, 2013; Quercia, Feiss, & Michel, 2013; Renvall, Lehtonen, & Hari, 2005). This theory does not suggest that dyslexic readers do not have difficulties with speech and phonological stimuli, but rather extends these phenomena to a perceptual deficit. As did previous studies, the
results of the present study also show that dyslexic readers demonstrate lesser ability in temporal processing tasks (longer TOJ thresholds) and score lower on reading and phonological awareness tests. Moreover, we also showed that improvement in auditory temporal processing, for both dyslexic and normal readers, was accompanied by an improvement in reading and phonological awareness. These results support the ATP theory and show relationship between ATP and phonological awareness regardless of the group tested.

As mentioned above, the ATP theory suggests that a perceptual deficit underlies the reading and phonological difficulties that dyslexic readers experience; specifically, a deficit in temporal processing. The present study, along with previous ones (Ahissar et al., 2000; Fostick et al., 2012a; Kujala, Lovio, Lepistö, Laasonen, & Näätänen, 2006), found comparable performance between dyslexic and normal readers in tasks manipulating perceptual abilities other than temporal processing. The importance of these findings is that they suggest that dyslexia does not reflect a general deficit in the perceptual system, as some of the abilities tested were not deficient. Rather, it suggests that dyslexia derives from a more specific deficit that relates to temporal processing, and to probably additional abilities that were not tested in the current study.

Moreover, in the present study, we used a "purely" temporal stimulus, without any spectral information or any other cues. Previous studies suggested that participants can employ different mechanisms when the temporal stimuli also include spectral characteristics (Ben-Artzi et al., 2005; Fostick & Babkoff, 2013). Therefore, we isolated the temporal characteristics of the stimuli, showing that even without any spectral information, these characteristics were related to reading ability and phonological awareness. Notably, however, stimuli with spectral information may be
less "temporal," but surely have higher resemblance to linguistic stimuli. Therefore, it remains unclear which stimuli are better for training purposes: ones with only temporal characteristics, which reflect the deficient mechanism for dyslexia, or the ones that also include spectral cues, which are similar to linguistic stimuli and therefore might better reflect the perceptual needs.

An interesting picture emerged when the percentage of change in different phonological tasks following TOJ training was compared. Although all tasks are considered as measuring the same ability, different amount of improvement was observed for the different tasks. In general, higher percentage of change was observed for pseudowords reading, than for phoneme deletion reaction time and then for phoneme deletion accuracy. These results might be due to differences between the tasks in difficulty level. Results close to ceiling effect in phoneme deletion can explain smaller change than in the pseudowords reading in which the initial accuracy level was around 25% for dyslexic readers and 65% for normal readers. Larger change in phoneme deletion reaction time than accuracy supports this explanation. However, the differences between these tasks can also reflect differences in the essence of the abilities required by each of them. While both tasks require good phonological awareness, they do not involve the same mechanisms. In pseudowords reading, the participants read written words, thus it relies on visual encoding and grapheme-to-phoneme representations. In phoneme deletion, the participants hear both the word and the phoneme needs to be omitted, using only auditory channels with no need to graphemes representation. These differences should be taken into account both in future research and clinical settings.

Although significant improvement was observed for dyslexic readers that had TOJ training, they still had very low accuracy level post-training. Indeed one of the
study's limitation was its rather short duration (5 consecutive days), and maybe longer training might resulted in higher accuracy levels. It also could be that the current training, in spite of its impressive results, is not enough. Since reading is a complex task, improving it should also include training in additional abilities, such as spectral and frequency discrimination, memory, and even attention. Multiple causes for dyslexia and complex training can also be the answer to the large inter-individual differences observed in dyslexia. The current study was focused more on the implications of training temporal processing. However, when considering improving reading ability, a larger scope of abilities should be employed.

In summary, the present study offers several contributions: (1) we found that dyslexic readers can be trained to improve their reading ability and phonological awareness; (2) training can occur in adult dyslexic readers, as well as in normal readers, not only in children; (3) auditory temporal processing is causally (although probably not conclusively) related to reading ability and phonological awareness, and improving such processing triggers better performance in reading and phonological awareness tasks; (4) the relationship between temporal processing, reading and phonological awareness is limited to specific abilities (such as temporal processing) and cannot be extended to general perceptual deficit (such as non-temporal processing); (5) temporal processing per se, with no other spectral information or cue, was found to be related to reading ability and phonological awareness, suggesting again that the temporal structure of the stimuli had an effect on reading ability and phonological awareness, in addition to the spectral cues in the linguistic stimuli.

The main purpose of the study was to establish a causal relationship between ATP and reading and phonological awareness. This goal was achieved by showing that when improvement in ATP was occurred, an improvement in reading ability and
phonological awareness followed. Another goal was to test the training effect of simple home-based computerized training systems, which apply temporal stimuli but no spectral cues. This goal was accomplished by means of the study design; however, further studies should re-test such and other training processes with longer training duration and a follow-up phase, as well as with other mechanisms.
References


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Figure 1. TOJ threshold for each study group by day. Only groups who were TOJ trained had TOJ threshold data at Days 2 to 4.
Figure 2. Intensity discrimination threshold for each study group by day. Only groups who had intensity discrimination training had threshold data at Days 2 to 4.
(a) Pseudowords reading

(b) Phoneme deletion accuracy
Figure 3. Scores on phonological awareness tasks for each study groups at Day 1 and Day 5 for (a) pseudowords reading; (b) phoneme deletion accuracy; and (c) phoneme deletion reaction time.
Figure 4. Percentage of change from Day 1 to Day 5 by study group for each task in the study. TOJ=temporal order judgment threshold; Int.Disc.=intensity discrimination threshold; pseudowords =number of pseudowords read correctly in 1 minute; Phon.Del.Acc=phoneme deletion accuracy; Phon.Del.RT= phoneme deletion reaction time.